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Quantifying Fire Risks in Pontianak for Future Planning and Development

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Abstract – Pontianak, a densely populated urban center divided by rivers into three distinct development zones, faces significant fire risk. This research delves into Pontianak's density and accessibility, aiming to craft a resilient city map to effectively combat fire disasters and bolster urban resilience. Its objective is to offer a comprehensive, evidence-based analysis of urban challenges, specifically related to fire risk. Employing a quantitative approach alongside grounded theory analysis, this study investigates how population density and accessibility intertwine within a designated grid. It involves calculating the total building area to establish population distribution and assessing city route accessibility using step-depth space syntax analysis. The results address potential threats, such as the absence of fire stations in certain areas, and underscore the city's weakness, specifically its ineffective accessibility. The output of this study is a gridded map that shows the risk level of each area in Pontianak, raising awareness among citizens and encouraging proactive measures, such as equipping homes with fire extinguishers and adopting fire-resistant materials during construction.

Keywords: *accessibility, density distribution, gridded map, space syntax*

I. INTRODUCTION

Fire, an uncontrollable outbreak of flames or smoke, poses significant risks to both lives and property, as acknowledged by the Ministry of Transportation in 2009. Its potential to jeopardize safety and wealth is particularly heightened in densely populated urban areas, where the uncontrolled spread of flames within residential areas leads to substantial losses in both property and human lives. To effectively address and mitigate such occurrences, comprehensive urban fire protection and prevention strategies become imperative. Urban fire protection management encompasses a holistic approach involving organizational systems, manpower, infrastructural facilities, and procedural frameworks aimed at preventing, mitigating, and minimizing the impact of fires on buildings, environments, and cities.

Cities characterized by high population densities face a pronounced vulnerability to fire disasters (Juriansyah & Fardani, 2023; Utama, 2020). This vulnerability is exacerbated by various factors, including diminished infrastructural quality and the surge in population resulting from rapid urbanization. The consequential strain on urban resources renders cities ill-prepared to effectively combat and manage building fires. Despite the pressing need for swift and precise fire management, the optimal performance of firefighting personnel is hindered by numerous impediments (Septreziera & Manik, 2013). Pontianak is situated in West Kalimantan as the province that has the second highest fire case in Indonesia (Uddin et al., 2021). Pontianak is boasting the highest population density of 6,110 individuals per square kilometer (BPS-Badan Pusat Statistik, 2021), compounded by its geographical location on the equator amidst peatlands (Sarwono, 2011). These environmental and demographic conditions significantly elevate Pontianak's susceptibility to fire disasters where 55 fire cases occurred in the year 2015 (Utama, 2020), a fact corroborated by data from the Regional Disaster Management Agency in 2015, which illustrates a higher frequency of residential fires in Pontianak compared to other cities in West Kalimantan.

In 2023, West Kalimantan experienced its worst forest and land wildfire record (Bafadal & Hestiantini, 2023; Oxtora, 2023). The Department of Meteorology, Climatology, and Geophysics suspects that the consecutive heavy rainfall in the preceding three years (2020, 2021, and 2022) led to a dry season in 2023, contributing to the heightened incidence of fires and wildfires (Apriliani, 2023). This phenomenon also occurred in 2016 when the land became dry and prone to wildfires (Permata et al., 2023). This recurring phenomenon poses a potential cyclic threat that may reoccur in the future. Moreover, the close proximity and shared wall typology of buildings, particularly in the market and central business areas, amplify the impact of fire accidents in Pontianak. A recent incident resulting from an electrical short circuit, for instance, led to the burning down of 40 shops and houses due to the density of structures in close proximity to one another (Cipta & Putri, 2023).

With the challenges and past experiences, Pontianak needs efficient firefighting operations that necessitate both swiftness and accuracy (Septreziera & Manik, 2013). The strategic placement planning of fire stations within the fire management zone crucially hinges on response-time standards to fire notifications within the designated area. According to technical guidelines for urban fire protection management (Menteri Pekerjaan Umum, 2009), the firefighting service area within each fire management zone should not exceed a travel distance of 7.5 kilometers, with a response time of fewer than 15 minutes. In Indonesia, the response time of fire departments to fire notifications should ideally not surpass 15 minutes. Moreover, areas with human habitation should be within protective reach of fire trucks, positioned within 2.5 kilometers and 3.5 kilometers, respectively. However, the bustling population in Pontianak contributes to traffic congestion, particularly at connecting routes separated by rivers, leading to moderate congestion across several roads (Masudi et al., 2017). Given the prevailing challenges and vulnerabilities in Pontianak, the necessity to develop strategies to mitigate potential fire disasters becomes increasingly evident. This idea was also mentioned in previous research by Utama (2016).

Prior studies on fire disasters have focused on analyzing urban accessibility (road networks) and density distribution patterns (Badi et al., 2022). The space syntax method, rooted in graph theory and urban morphology, provides a quantitative framework for describing and measuring a city's spatial configuration, specifically in terms of its road networks (Baran et al., 2008). This approach facilitates the analysis of social, economic, and environmental aspects within spatial relationships, mathematically interpreting human behavior (Hillier & Hanson, 1984). Furthermore, evaluating a city's resilience significantly benefits from statistically and quantitatively mapped population distributions. Population maps serve as critical tools for measuring the impact of population growth, analyzing distances between populations and vital resources such as water supplies, assessing population impact, and supporting epidemiological studies (Dong et al., 2017). Addressing the optimal location of fire stations involves considering regions at high risk of fires and ensuring adequate accessibility and maneuverability for firefighting fleets as both preventive measures and firefighting strategies (Sutaryo & Suryadi, 2019). The challenges concerning facility location can be effectively managed by assessing the proximity of firefighting facilities to surrounding buildings and establishing efficient traversal routes.

In the course of this research, the morphological structure of Pontianak will be examined quantitatively concerning fire disasters. This analysis will focus on vulnerability data derived from two primary factors: building density and accessibility for firefighting services. It will involve meticulous

analysis using population data per grid and will implement the space syntax method. The quantitative findings will serve as a comprehensive reference for conducting an in-depth quantitative analysis of urban challenges, thereby facilitating the proposal of a resilient Pontianak city concept. The ultimate goal is to design and develop a resilient city map for Pontianak to effectively combat fire disasters and enhance overall urban resilience.

II. METHODS

The research methodology involves a quantitative approach combined with grounded theory analysis to draw comprehensive conclusions. The core investigation centers on understanding how population density and accessibility relate within a designated grid. To achieve this, the study is divided into two simultaneous tasks. First, it delves into establishing the distribution of the population within the grid. This step is accomplished by calculating the total area of buildings within Pontianak. The second task focuses on evaluating city route accessibility using step-depth space syntax analysis to compute the distance between each fire station and all road segments. Both tasks primarily adopt quantitative approaches.

The research begins with a detailed data collection and analysis phase, utilizing statistical techniques to map population distribution within the grid. Additionally, it employs space syntax methodology to assess road accessibility, maps fire station locations, and determines the optimal distances needed for fire facilities to cover all buildings or the service coverage (Yao et al., 2019). These analytical tasks provide data for quadrant mapping and partial correlation analysis. To effectively communicate the findings, the research uses color-coded maps within defined ranges to present information in a clear and informative manner.

The maps are presented in a gridded format. While the global standard typically employs thirty arc seconds or 1 kilometer (Doxsey-Whitfield et al., 2015), this study utilizes a more refined grid size of 0.5 kilometers. This increased level of detail divides the city area into 484 grid units, allowing for a more intricate analysis. Despite Pontianak's actual area being 118.31 square kilometers, adjustments are made due to network disconnections, expanding the total area under consideration to 121 square kilometers. To simplify the density mapping process, each grid unit is designated with alphanumeric labels.

The study concentrates on Pontianak City in Indonesia, recognized as the most densely populated city in West Kalimantan Province, hosting 658,685 residents at a density of 5,567 individuals per square kilometer (BPS Kota Pontianak, 2021). The investigation focuses on Pontianak's administrative area, covering 107.8 square kilometers. The city's geographical layout is characterized by the Great Kapuas River, the Small Kapuas River, the Landak River, and the equator line intersecting the area. The city is divided into three land masses by these rivers, forming a Y-shaped structure, with the largest land mass further divided into four districts, making a total of six districts within Pontianak. To facilitate river crossings, there are two bridges and a ferry service available. Positioned on the equator, Pontianak experiences a hot and humid climate, with elevations ranging from 0.10 meters to 1.50 meters above sea level and land inclinations around 0 - 2%.

III. RESULT

The evaluation conducted to assess the fire safety of the city resulted in significant findings across two primary factors: density distribution, accessibility of firefighters, and the interrelation between these factor elements. Through detailed gridded maps, as specified in the aims and methods, these categories offer a substantial reference and evidence-based framework. These findings serve as evidence for conducting an in-depth quantitative analysis of urban challenges, specifically targeting fire risk within the city.

A. Density Distribution in Pontianak

The analysis of density distribution involved a detailed examination of gridded maps, specifically focusing on the quantification of built-up areas derived from OpenStreetMap's building footprint data. This allowed us to create a density map highlighting regions with concentrated built-up areas. The map vividly illustrates that high-density areas primarily cluster around the riverbanks, forming a significant correlation between population density and proximity to the river (see Figure 1). The strip of non-built-

up, delineated by a blue line, serves as a natural division between the north and west districts, representing the river area.

Notably, areas closer to the river exhibit a marked increase in density, gradually tapering off as distance from the riverbank increases. The west district stands out with a conspicuous spike in density, indicating a localized concentration of built-up spaces. Meanwhile, the central zone boasts the highest average density across the surveyed area. Conversely, the north area displays the lowest average density, comprising a substantial number of grid tiles devoid of any built-up structures. This observation highlights the sparse population distribution in this particular region.

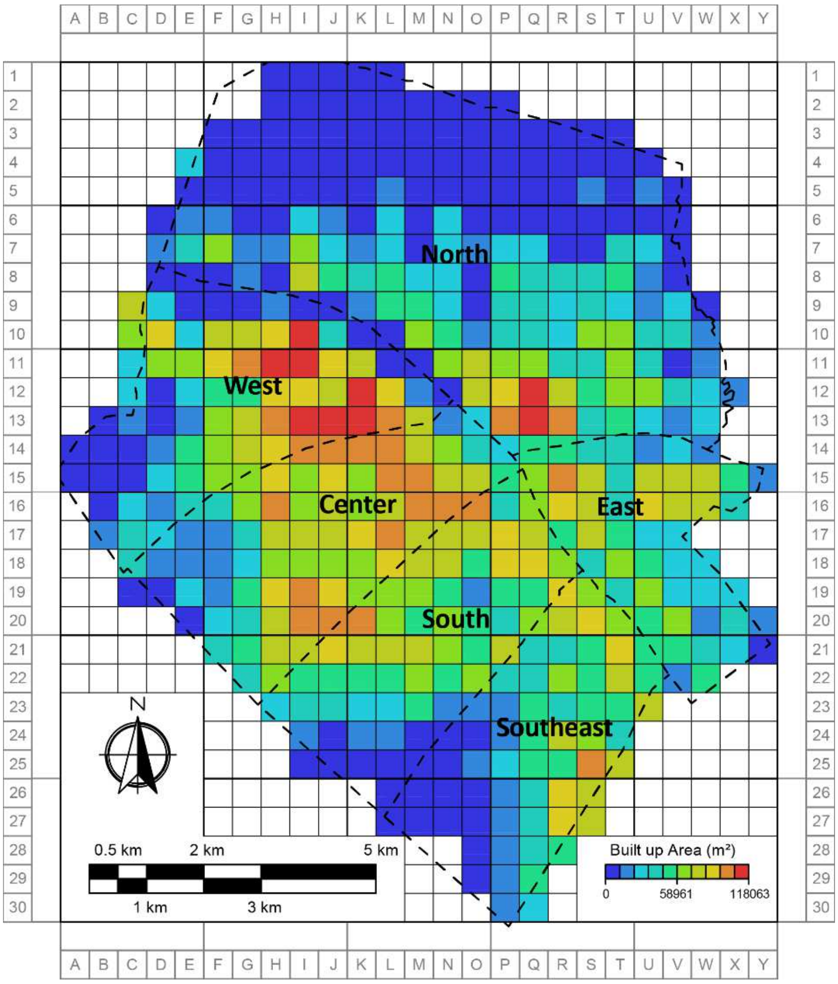

Fig. 1. Gridded map of built-up area in Pontianak
Source: Authors (2023)

The implications of these findings for fire risk assessment are significant. Given that high-density areas predominantly align with the riverbanks, it is crucial for fire stations to strategically cover these densely populated zones. The concentration of built-up areas in proximity to the river elevates the fire risk in these regions, necessitating a robust fire protection strategy. Therefore, allocating additional resources and reinforcing fire protection efforts in the high-density areas along the riverbanks becomes imperative. By enhancing coverage in these regions, fire stations can better address the heightened fire risk associated with densely populated areas, ultimately fostering improved safety and protection for these communities.

B. Accessibility of Fire stations in Pontianak

Pontianak hosts 39 fire stations (see Figure 2), distributed across 6 districts as follows: 7 stations in North Pontianak, 6 in East Pontianak, 2 in Southeast Pontianak, 9 in South Pontianak, 7 in Central Pontianak, and 8 in West Pontianak. In this study, the analysis area spans a radius of 9 kilometers within Pontianak, encompassing the surrounding regions within the analysis. Based on this radius, an additional 4 fire stations from Kubu Raya Regency were included in the analysis. One station is adjacent to East

Pontianak, while the other 3 are near Southeast Pontianak. Together with these additional stations, the total number of fire stations considered in this analysis amounts to 43 (see Table 1). Data regarding these fire stations were sourced from the Pontianak City Communication and Information Office website. The locations of these fire stations were pinpointed on the map of Pontianak using Google Maps (see Figure 2). As per this data, not all neighborhoods within Pontianak have fire stations. In fact, several stations are centralized within specific neighborhoods only.

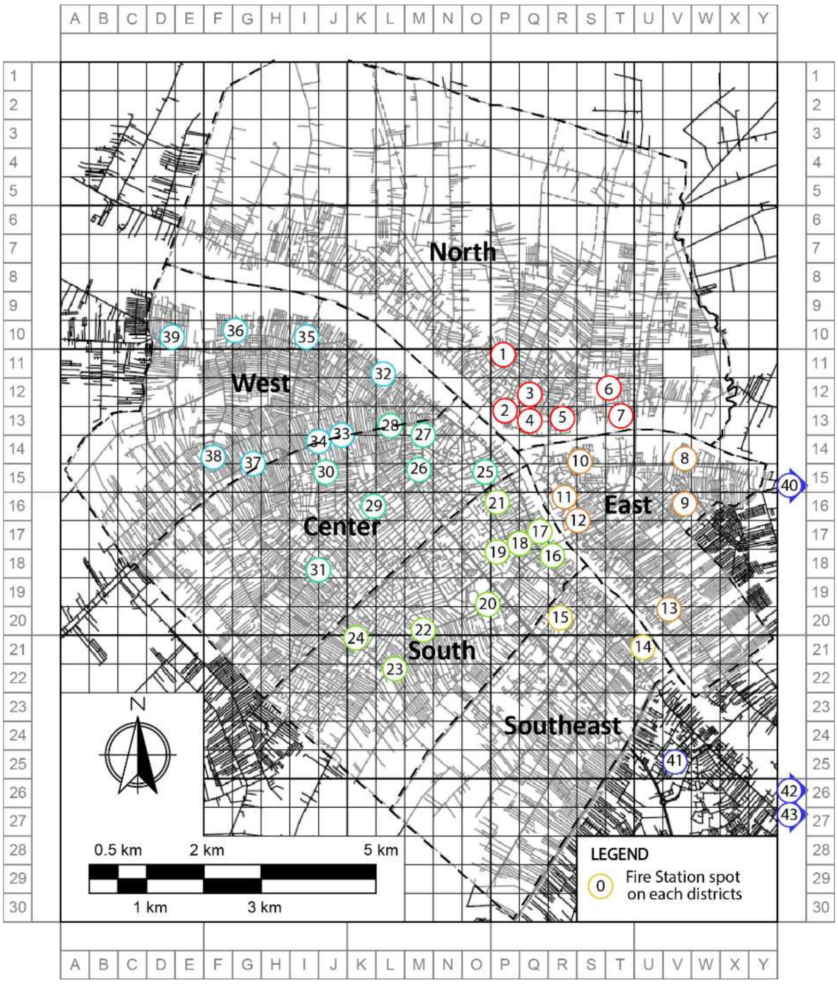

Fig. 2. Fire station distribution in Pontianak
Source: Authors (2023)

The analysis of firefighting routes entails assessing the accessibility of fire stations concerning the surrounding buildings. This analysis aims to evaluate the feasibility of these station locations in response to potential fire scenarios in Pontianak . Assessing the accessibility of fire stations is aided by space syntax analysis using step-depth analysis, showcasing topographic depth. The step-depth analysis calculates the distance or depth of buildings concerning fire stations. The depth is represented in a round number. The farther a building is from the fire station, the higher the number of step-depth values. For buildings close to fire stations, the step-depth value tends to be around 1.

The results of the step-depth analysis reveal that the average depth in Pontianak stands at 5.41 (see Figure 3). This implies that, on average, fire stations can be reached within the city with five turns. To easier to spot the depth of the area in Pontianak , the result of step-depth was converted to a gridded map (see Figure 4). This figure is lower than its median value of 8.5. Approximately 80.8% of the area in Pontianak exhibits a step-depth value below the median. Hence, on average, Pontianak is reasonably well-equipped to handle fires. However, some points in Pontianak are challenging for firefighting access. The difficult-to-reach areas for fire stations encompass 19.2% of Pontianak's total area (see Figure 3). The analysis highlights these points in North Pontianak and East Pontianak.

Table 1. Fire station distribution in Pontianak City and Kubu Raya Regency

No	District	Number of fire station
1	North Pontianak	7
2	East Pontianak	6
3	Southeast Pontianak	2
4	South Pontianak	9
5	Central Pontianak	7
6	West Pontianak	8
7	Kubu Raya (Outside Pontianak)	4
	Total	43

Source: Authors (2023)

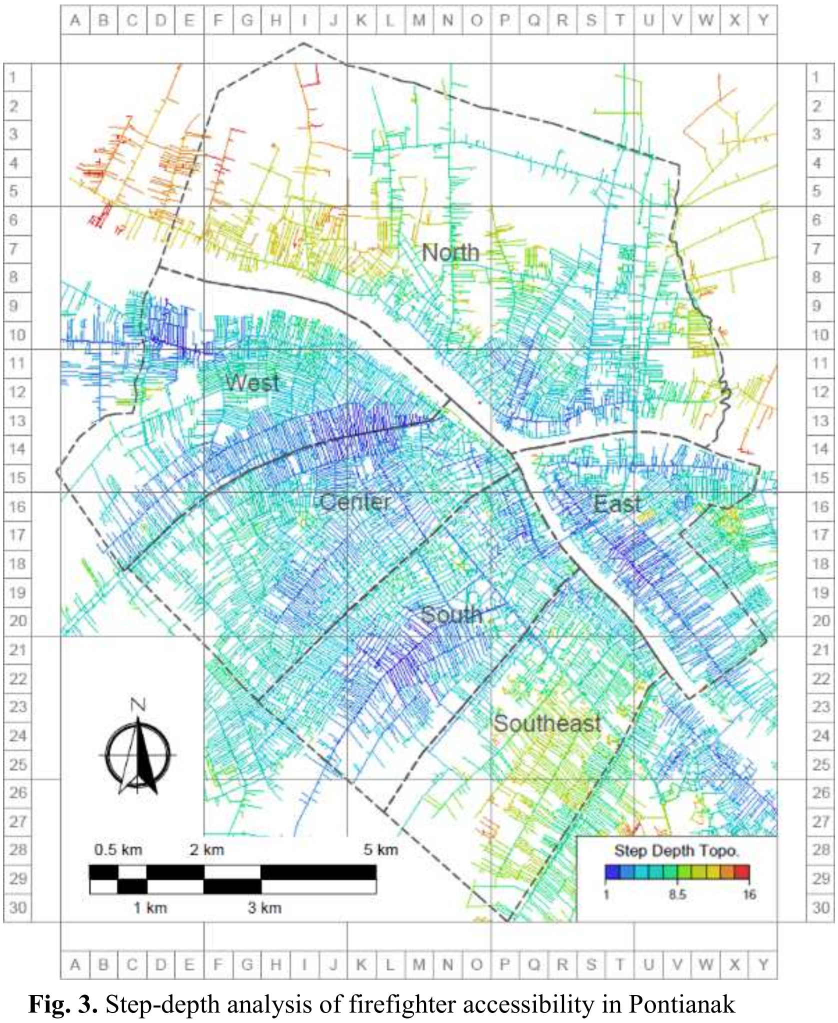

Fig. 3. Step-depth analysis of firefighter accessibility in Pontianak
Source: Authors (2023)

Accessibility challenges in North Pontianak stem from firefighting access limitations from other districts due to the barriers posed by the Kapuas and Landak Rivers. Apart from the fire stations in North Pontianak itself, only the stations in East Pontianak have relatively close access to North Pontianak. The distribution of fire stations in North Pontianak is uneven across all neighborhoods. These stations are clustered in the neighborhoods, near the river. The most challenging points are found in the Batu Layang neighborhood in the western part of North Pontianak, which lacks fire stations.

The accessibility depth in Southeast Pontianak also indicates higher difficulty or challenging access. This arises from the smaller number of fire stations compared to other districts. Southeast Pontianak has 2 fire stations, whereas the average number of stations in all districts is 6.5 (see Figure 4). This suggests the necessity to augment fire stations in Southeast Pontianak. From the conditions

observed in North Pontianak and Southeast Pontianak, it is evident that aside from the positions of fire stations, other factors contribute to a region's difficulty in accessing fire stations. These factors include river accessibility, distance from the city center, and bridge positions. From this analysis, points farther from the river exhibit higher step-depth values. This is because Pontianak developed from the riverside towards the inland areas.

Consequently, the transportation facilities along the riverbanks are more developed and integrated. North Pontianak and Southeast Pontianak, being distant from the city center, exhibit higher depths. Areas further from the city center are more segregated, making it increasingly challenging for fire stations from different districts to reach these locations. In contrast to these districts, West Pontianak appears structurally situated on the city's edge but is well-integrated with Central Pontianak. Another reason for West Pontianak's good accessibility for fire stations is the ample number of stations, totaling 8 points.

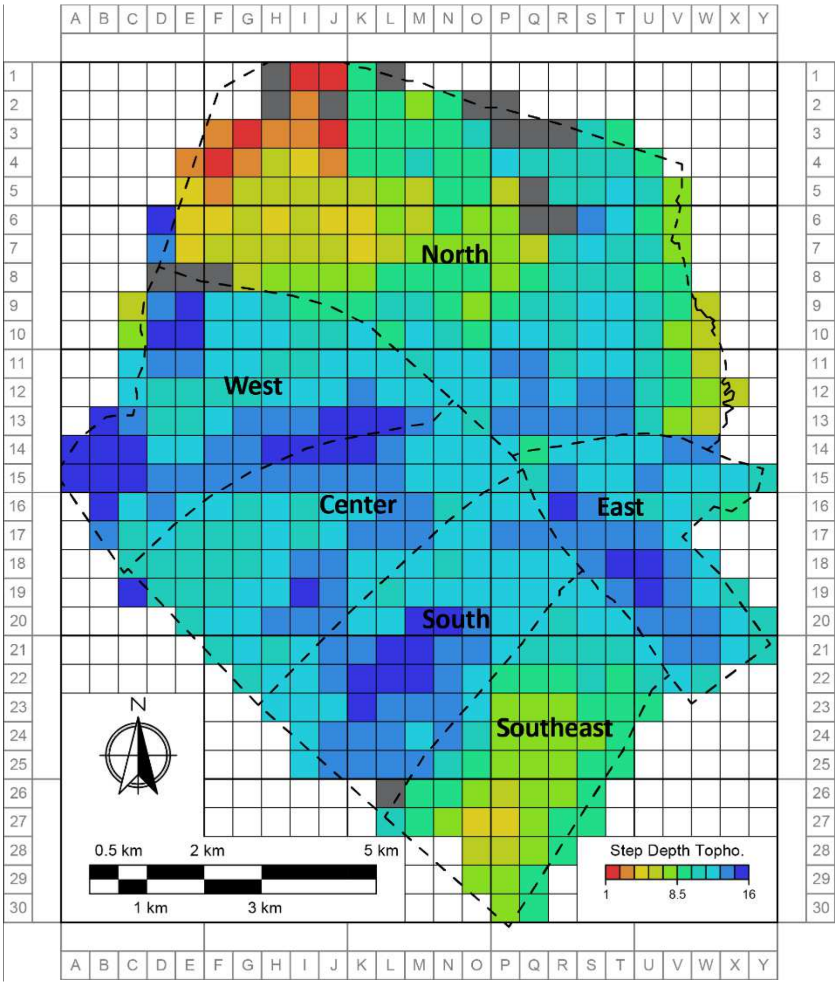

Fig. 4. Gridded map of Step-depth analysis in Pontianak
Source: Authors (2023)

C. Fireproofing Pontianak through a correlation between density and accessibility

In this study, step-depth data is put side by side with building density data to assess an area's vulnerability to fires. The building density data aligns with population density data per grid using square meters for building area. Both data types are compared in quadrant diagrams, representing the resilience conditions of a grid or area against fires. The resilience levels are categorized into 3: high, moderate, and low. Areas with high building densities and high step depth to fire stations indicate easy fire spread and delayed fire station arrival, classifying these areas in quadrant 1 (Q1). Conversely, areas with low building densities (below the median) and easily accessible fire stations (step depth below the median) signify high fire resilience, where fire spread is more challenging, and fire stations can quickly handle fire incidents, categorized in quadrant 3 (Q3). Furthermore, areas near fire stations but densely packed with buildings are classified in quadrant 4 (Q4), indicating moderate fire resilience due to the high risk

of fire propagation. The last category includes areas far from fire stations with low building density, classified in quadrant 2 (Q2). Fire resilience in quadrant 2 is moderate as these areas are challenging for fire station accessibility.

The results from the two quadrant maps indicate that a significant portion of Pontianak exhibits high fire resilience. Based on building area, 50% of Pontianak displays high fire resilience (quadrant three), and it reaches 75% when considering the number of buildings. However, there are also several areas in Pontianak with moderate fire resilience. In the quadrant map based on building areas, 30% of grids fall into quadrant 4, and 18% into quadrant 3. Meanwhile, the percentage based on the area in the quadrant map is smaller, with 6% falling into quadrant 4 and 19% into quadrant 2. Only 1% of Pontianak exhibits low fire resilience, situated in North Pontianak and South Pontianak. These points are distant from fire stations and have high building densities.

The study conducted a partial correlation between building mass distribution and fire station accessibility to understand urban development phenomena concerning fire resilience. The results show that the correlation coefficient between building distribution based on area and fire station step depth is -36.3% (see Figure 5). Similarly, the correlation coefficient between building distribution based on quantity and fire station step depth is -35.5%. Both coefficients indicate a moderate negative correlation between these paired variables. The scatter plot pattern reflects that densely built areas are closer to fire stations, suggesting Pontianak's consideration of fire disasters. The city demonstrates responsiveness in enhancing firefighting-related infrastructure.

Fig. 5. Scatter Plot and correlation between built-up area and step-depth in Pontianak
Source: Authors (2023)

In the quadrant diagram (see Figure 6), both quadrant 2 and quadrant 4 exhibit moderate fire resilience levels. The similarity in these levels suggests the equal importance of fire station accessibility and building density. There are two solutions to address fire station accessibility throughout Pontianak. The first solution is to add fire stations at indicated red points in Batu Layang neighborhood, North Pontianak, and Bangka Belitung Darat neighborhood, South Pontianak. Based on distance and building count, these neighborhoods are recommended to add 2 fire station points each. The second solution involves altering Pontianak's road network structure. Changing these road routes is expected to assist fire stations in reaching fire-affected areas. Improving the road route for North Pontianak would be easier with a bridge connecting North Pontianak to West Pontianak. This is considering that West Pontianak has 8 fire station points, 3 of which are near the Kapuas River. A suggestion to improve fire station accessibility in Southeast Pontianak is to enhance road interconnectivity in areas distant from the river. The upper part of Pontianak seems poorly interconnected between its districts. Creating an outer ring road in the upper part of Pontianak is recommended to facilitate movement between districts.

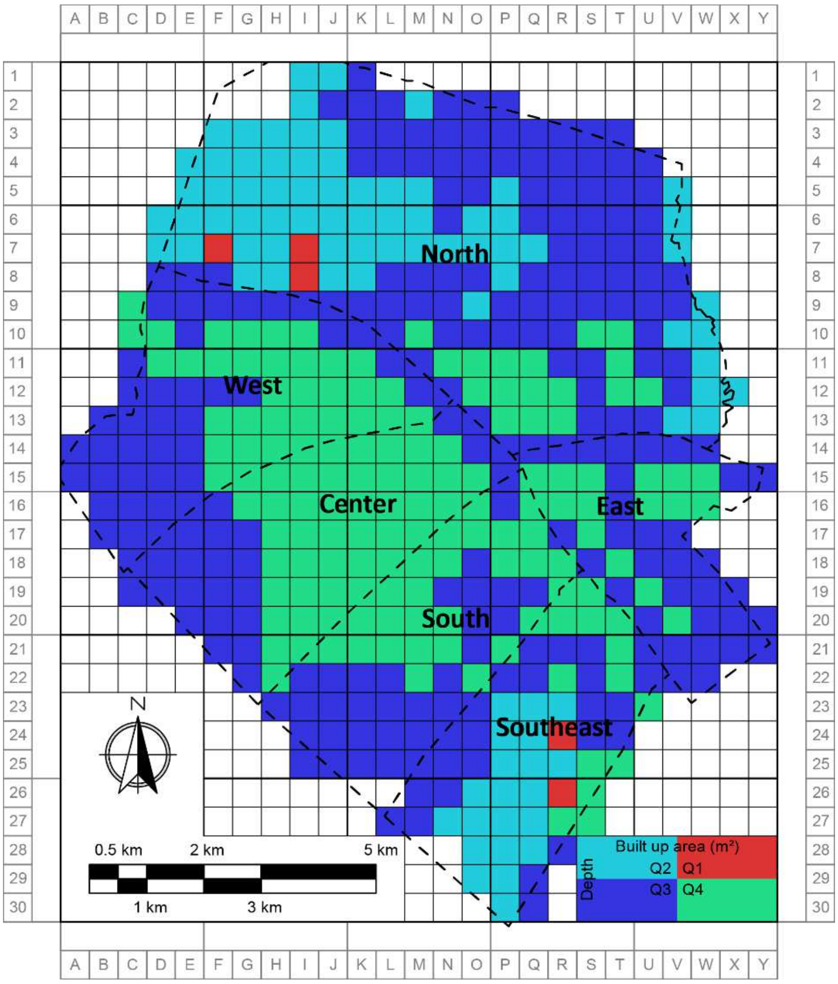

Fig. 6. Scatter Plot and correlation between built-up area and step-depth in Pontianak
Source: Authors (2023)

IV. DISCUSSION

In conducting research aimed at identifying vulnerable areas susceptible to fire risk, the selection of variables plays a pivotal role. Previous studies have employed contrasting variables, as evidenced by Utama (2020), who utilized economic variables to locate vulnerability, positing that economically disadvantaged individuals find it challenging to recover from fire incidents. This perspective resulted in identifying North Pontianak and East Pontianak as high-risk areas. However, this research diverges from recovery-focused variables, prioritizing variables associated with risk assessment rather than recoverability.

Identifying vulnerable areas precedes the quantification of strategies to minimize firefighting response times, a factor recognized in prior studies such as those conducted by Oh et al. (2019) and Tao et al. (2023). Utilizing step-depth analysis to measure the distance between fire stations and potential fire risk areas proves notably efficient. This approach contrasts with Renkas et al. (2022) use of Voronoi diagrams, which, while efficient in measuring distance, lack direct relevance to a city's accessibility. Addressing the limitations of earlier studies, this research endeavors to comprehensively map all street segments in Pontianak using the space syntax method. This approach counters the shortcomings of Utami et al. (2014) research, which identified the shortest paths for firefighter vehicle movement but was constrained to only 49 designated points. The complexity of Pontianak's route system and the random nature of fire accidents rendered previous approaches ineffective in optimizing optimal paths.

Employing quadrant maps reveals substantial areas in Pontianak exhibiting high fire resilience, strengthening the correlation between factors and fire risk assessment. This contrasts with Yao et al. (2019), whose study primarily focused on location and accessibility factors while neglecting building density distribution—a critical element in this analysis. Unlike Supriadi and Oswari (2020), who focused

solely on prone areas based on public reports, this research acknowledges all areas' potential fire risks, prioritizing densified regions.

Comparatively, while Badi et al. (2022) and this study pinpoint potential fire station locations to enhance service coverage, the latter also justifies vulnerability through mapping—an essential aspect of evidence-based decision-making. Similarly, Sarwono's (2011) research on fire station placement from 22 years ago still echoes the need for additional stations around North Pontianak, albeit with some areas now equipped with fire stations. Yet, Southeast Pontianak remains unaddressed, suggesting the need for a station inland in grid R24 or R26. Numerous attempts have been made to map fire risk in Pontianak. Juriansyah and Fardani (2023), for instance, utilized fire case data and a scoring system but arrived at contradictory results compared to this research. They identified East, Central, and South Pontianak as vulnerable areas, whereas this study points to Southeast and North Pontianak.

In the context of Pontianak, previous efforts to map fire risk lacked data completeness and accuracy. For instance, Nurhidayati (2016) focused solely on East Pontianak, while Utama (2014) concentrated on South Pontianak. In contrast, this study encompasses the entire city, providing a more comprehensive dataset. Additionally, Juriansyah and Fardani's (2023) subdivision of Pontianak into 29 zones contrasts with this research, which subdivides Pontianak into 484 grid tiles, offering significantly more detailed and accurate data.

The study holds significant potential benefits for both authorities and the public in enhancing urban resilience. The results highlight potential threats, such as the absence of fire stations in certain areas, and underscore the city's weakness, specifically its ineffective accessibility. This study aids in providing analyses and data to enhance the resilience of Pontianak for future development. For the public, the study offers maps that assess the fire resilience of each area, serving as an educational tool on the importance of fire resilience in the city. Specifically for the citizens of Pontianak, this study raises awareness of the potential threat of fire accidents in their respective areas. Residents can respond to this by equipping their homes with fire extinguishers. Additionally, the public can adopt fire-resistant materials or take preventive measures to contain the spread of fire when constructing houses.

This research distinguishes itself through its emphasis on risk-centric variables, advanced mapping methodologies, and a detailed assessment of Pontianak's fire risk, addressing critical gaps in prior studies. The comprehensive evaluation spans the entire city, utilizing 484 grid tiles, yielding highly detailed and precise data. This enables authorities to identify vulnerable areas with greater accuracy. The study's unique focus on fire resilience in densified regions provides insights for informed urban planning strategies. Through evidence-based decision-making via mapping, the research aids authorities in optimizing fire station locations and justifying vulnerability assessments. In essence, the study significantly contributes to Pontianak's urban resilience by offering a comprehensive depiction of fire risk, guiding the development of effective strategies and policies to minimize risks and enhance overall city resilience.

V. CONCLUSION

Understanding the accurate population distribution within a city aids in urban disaster planning and preparedness. This research crafted a more detailed population grid map for assessing accessibility. The findings revealed the nuanced population spread of Pontianak. Density grids reflected dispersed density concentrations from riversides to inland areas. The quadrant map depicted Pontianak 's favorable accessibility, offering recommendations for urban development. By dividing into quadrants, authorities can concentrate resources to improve or develop low-accessibility network units. For instance, one grid unit exhibited low accessibility, distant from the city center but with high population density. With correlation coefficients of 40.5% and 50.9%, this study identified a moderate positive correlation between density distribution and accessibility.

On average, Pontianak demonstrates moderate fire resilience. Dominantly, a significant portion exhibits high fire resilience. Correlation analysis indicates that densely populated areas generally have nearby fire stations. However, 19.2% of areas are distant from fire stations, and 1% of the city areas with dense building mass exhibit low fire resilience. These areas lack fire stations and are affected by three factors: accessibility from rivers, distance from the city center, and bridge positioning. Enhancing fire resilience in Pontianak involves augmenting fire stations in Quadrant 1 (Q1) and enforcing fire

protection regulations in Quadrant 1 (Q1) and Quadrant 4 (Q4), highly and moderately recommended respectively.

This study yielded Pontianak's population and building distribution data, versatile for extensive analyses beyond fire scenarios. It allows disaster impact assessment or mitigation scenario planning for Pontianak. Future research is encouraged to utilize Geographic Information System (GIS) technology for data presentation, expediting processing, and facilitating various analyses. Currently, spreadsheet tools analyze data, and Computer-Aided Design (CAD) is used for data modeling. GIS, offering space syntax analysis tools, such as Q-GIS plugins, would significantly enhance analytical possibilities.

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